Olga Ovchinnikov is a sophomore at the University of Tennessee, Knoxville, where she is majoring in Physics and minoring in Biochemistry. Over the past year Olga has been conducting research in the area of Chemical Physics, performing experiments with the fullerene C60, at the University of Tennessee. During her appointment at LBNL Olga participated in the first ever photoionization study of Iron IV using the merged-beams technique and the photon beam from the Advanced Light Source. As a result of her experience at LBNL, Olga plans to attend graduate school in physics and attain a Ph.D.

Fred Schlachter is a staff scientist at the Advanced Light Source, Lawrence Berkeley National Lab. He received his education in physics at the University of California in Berkeley and the University of Wisconsin in Madison. He worked for several years in France at Saclay and the University of Paris. Fred has done research in atomic and molecular physics at Berkeley Lab for the past 25 years, most recently studying quantum chaos, molecular fragmentation, and photoionization of ionized matter. Alongside his research publications is an article in Scientific American on ultrabright synchrotron light sources.

PHOTOIONIZATION OF FE^{3+} IONS

OLGA OVCHINNIKOV AND FRED SCHLACHTER

ABSTRACT

Photoionization of Fe^{3+} ions was studied for the first time using synchrotron radiation from the Advanced Light Source (ALS) and the merged-beams technique. Fe^{3+} ions were successfully produced using ferrocene in an electron cyclotron resonance ion source (ECR). The measured yield of Fe^{4+} photoions as a function of photon energy revealed the presence of resonances that correspond to excitation of autoionizing states. These resonances are superimposed upon the photoion yield produced by direct photoionization, which is a smooth, slowly decreasing function of energy. The spectra for the photoionization of Fe^{3+} will be analyzed and compared with theory. The data collected will also serve to test models for the propagation of light through ionized matter.

INTRODUCTION

Almost all the information we receive about our universe comes from light from distant stars, and more than 99% of the matter in the universe is found in ionized form. Therefore studies of photoionization of ions provide data for the modeling of propagation of light through space, which is critical for our understanding of the universe. The photoionization of ions is the removal of one or more electrons by absorbing energy from light radiation (photons). In our experiment one-electron photoionization of ions was observed.

Iron is a common element not only on earth but also in the universe. In interstellar space, iron mainly exists in ionized form and can readily undergo photoionization by the radiation of stars, quasars, and other astronomical occurrences. Therefore the light that we receive could be affected by photoionization and thus it is necessary to study and understand the photoionization process of ions.

A third-generation synchrotron light source contains insertion devices called undulators that create photon beams in a narrow energy and angular range, producing an intense, nearly parallel light beam. Using the synchrotron radiation from the third-generation Advanced Light Source (ALS) and the merged-beams technique(Covington et al 2002) it was possible to observe the photoionization of Fe^{3+} for the first time.

There are two mechanisms of photoionization of Fe^{3+}. One is direct photoionization that serves as a background, rising from zero as a step function at the ionization energy threshold and falling smoothly with increasing photon energy (Figure 1),

The second is the indirect process and is characterized by excitation of Fe^{3+} to a doubly excited intermediate state that decays spontaneously by a process called autoionization, ejecting an electron:

This process gives rise to resonances occurring at varying photon energies that correspond to the excitation of autoionizing states. Interference between the direct and indirect photoionization pathways yields asymmetric resonance line shapes.

Measurement of these processes is crucial to our understanding of the universe. However until recently it was very difficult to obtain experimental data on these phenom-

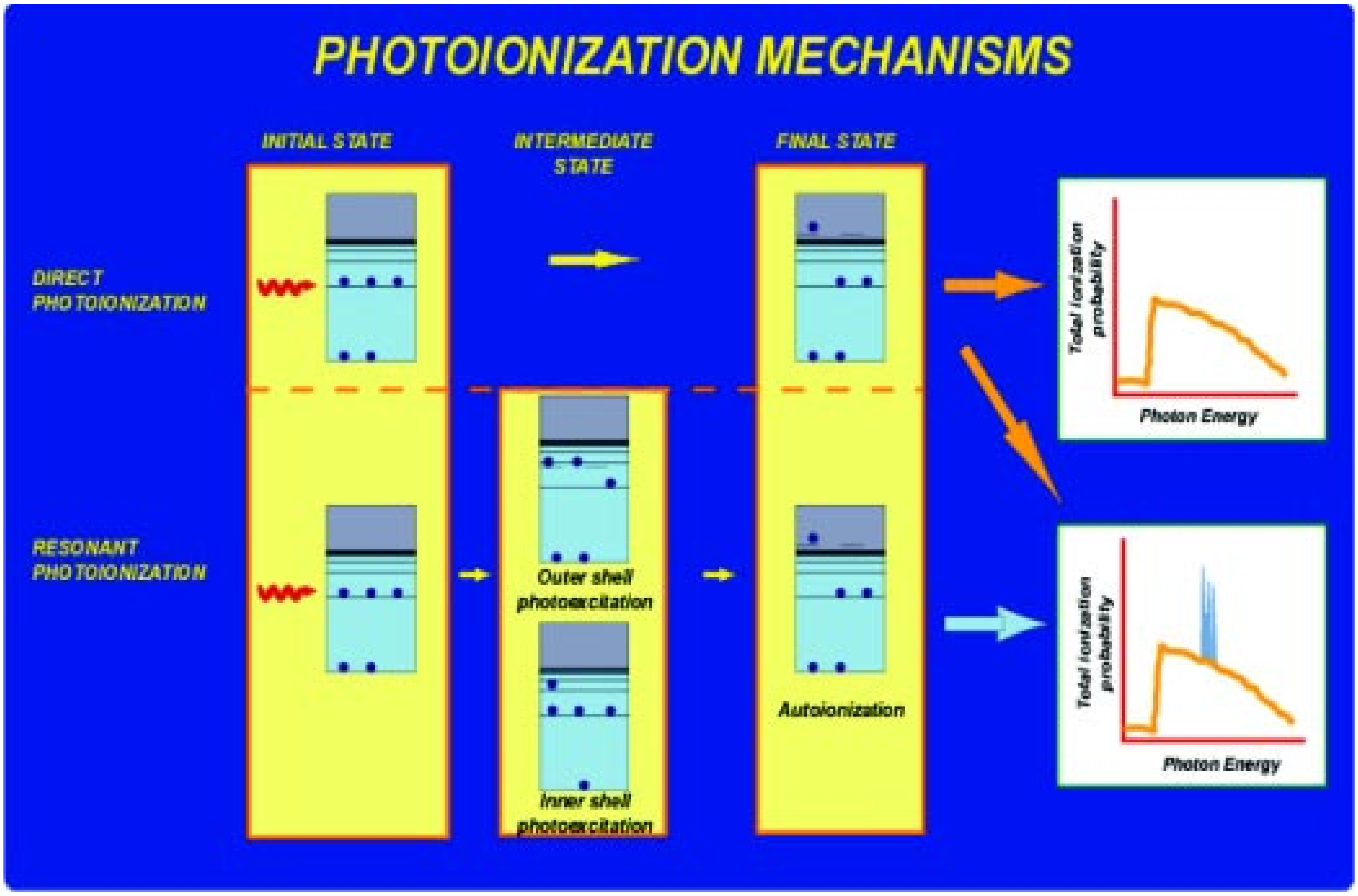

Figure 1: Diagram for the photoionization process. As may be seen from the diagram there are two processes involved in photoionization. The direct process creates the smooth background while the indirect process is responsible for the resonance structure observed in photoionization.

ena due to the technical difficulty of producing ion and photon beam of sufficient density. These problems have been largely overcome by combining third-generation synchrotron radiation sources and the merged-beams technique.

METHODS

The photoionization measurements were based on the merged-beams technique. The photon beam was produced by an undulator at the ALS Beamline 10.0.1 (Figure 2). A grazing incidence monochromator selected a collimated photon beam with a radius of less than 0.5 mm and a flux of up to 10^{13} photons/second over an energy range of 17-340 eV. The spectral resolution of the light exiting the monochromator was selected by adjusting the entrance and exit slits (Figure 2). The photon beam was chopped, which separated photoions from other ions created by interactions with residual gas in the merged path. The flux of the photons was measured by a silicon X-ray photodiode in the beamline, for which the average value was found to be 2-3 x 10^{13} photons/second. The current of the photodiode was directed to a current amplifier, whose analog output was sent to a voltage-to-frequency converter, which provided counts to a scaler in the data acquisition computer.

The Fe^{3+} target ions were produced by the evaporation of ferrocene, which was directed in gaseous form to an all permanent-magnet electron cyclotron resonance ion source (ECR) (Müller et al 2002). The ion beam was accelerated through a potential difference of 6 kV, focused and directed using a series of cylindrical electrostatic einzel lenses and steering plates (Figure 3). The cross-sectional area was defined by adjusting vertical and horizontal beam-defining slits located downstream of the analyzing magnet.

The 18 keV Fe^{3+} ion beam was merged onto the counter-propagating photon beam using a 90° spherical-sector electrostatic deflector. The spatial overlap of the ion and photon beams was optimized by the use of two sets of perpendicular electrostatic steering plates located before the merger plates. The interaction region is defined by a stainless-steel-mesh cylinder whose entrance and exit apertures are separated by 29.4 cm. In order to energy-label the photoions produced inside the interaction region, an electrical potential of +1.7 kV was applied. The two-dimensional overlap of both beams was observed by rotating-wire beam profile monitors located directly before and after the interaction region and a scanning slit located in the interaction region (Figure 4).

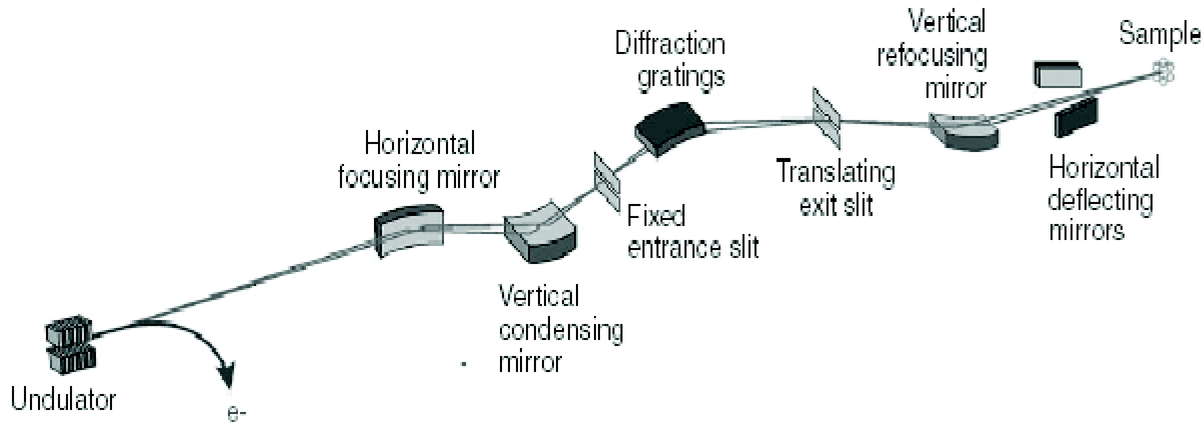

Figure 2: Schematic layout of ALS beamline 10.0.1 optics.

The Fe^{4+} photoionization products were separated from the parent Fe^{3+} beam by a 45° dipole-analyzing magnet located after the interaction region (Figure 3). The parent Fe^{3+} beam was collected in an extended Faraday cup connected to a current amplifier, whose analog output was sent to a voltage-to-frequency converter, which provided counts to a scaler in the data acquisition computer.

The Fe^{4+} products were directed through a small opening at the top of the Faraday cup to a 90° spherical electrostatic deflector, and onto a stainless steel plate biased to -550 V. The secondary electrons produced by the collision of Fe^{4+} ions with the stainless steel plate were directed to a microchannel-plate detector, which generated an electrical pulse for each Fe^{4+} ion. This pulse was sent to an amplifier followed by a single-channel analyzer, which set a threshold level to reject background electronic noise. The signal pulses were sent to a scaler in the data acquisition computer.

RESULTS

Using the merged-beam technique and synchrotron radiation, the photoion yield of Fe^{4+} was measured at a constant resolution of 40 meV from 43.5 to 62.5 eV. These data were taken with step sizes of 4 meV (Figure 5). The spectrum is divided into 3 different energy regions. The first region, 43.5 to 50 eV, shows three resonances with decaying intensities implying the presence of a Rydberg series (Figure 5). Further analysis complemented with atomic structure calculations will be needed in order to identify the nature of these resonances. The second energy range, from 50 to 55.5 eV, is primarily dominated by the direct photoionization process, although the presence of weak structure can be distinguished (Figure 5). Finally, the last section of data from 55.5 to 62.5 eV shows a dramatic increase in the

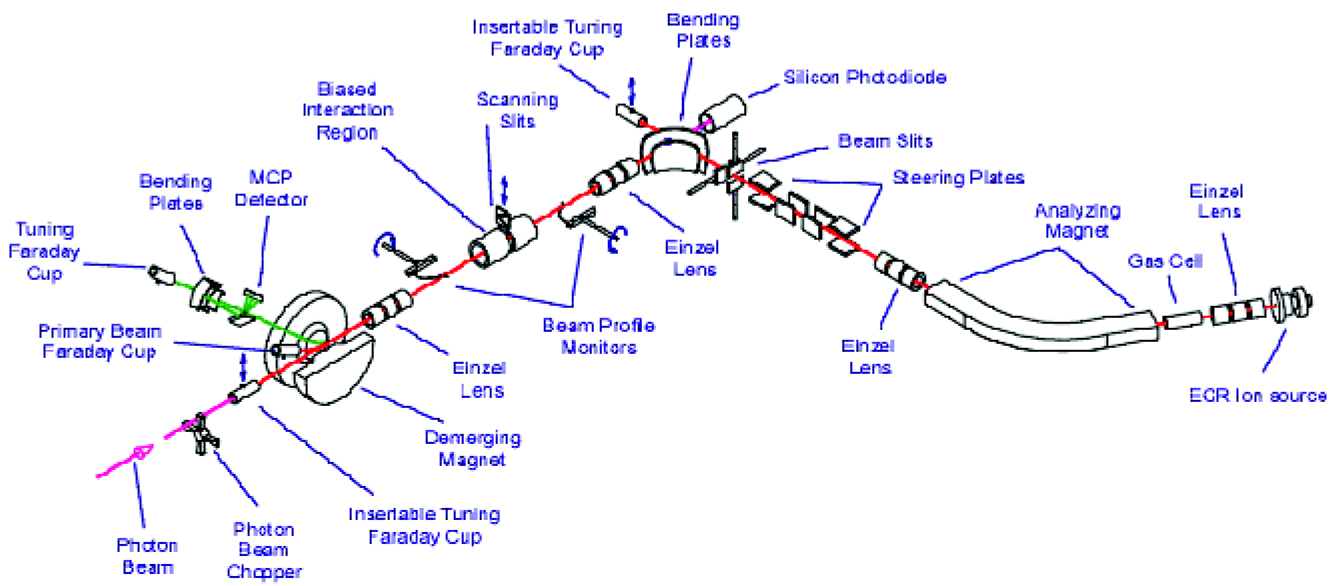

Figure 3: Ion Photon Beam (IPB) endstation installed at the ALS beamline 10.0.1

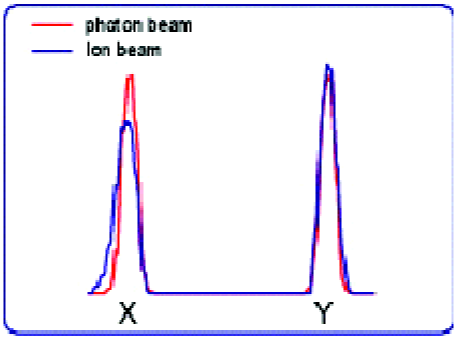

Figure 4: Two-dimentional spatial overlap profile of a photon and an ion beam.

photoion yield starting at 56 eV (Figure 5). Such increases of the photoion yields are common in the photoionization of positive ions when new channels open or thresholds for metastable species are reached. However, in this case the slope of increase of photoion yield is very smooth and gradual with energy, compared to the abrupt rise expected at a threshold. Furthermore, the photoion yield begins to decrease at 61 eV, suggesting the presence of an extremely broad resonance, corresponding to creation of a short-lived state that decays rapidly by the process of autoionization.

This experiment demonstrated the feasibility of studying experimentally the photoionization of an astrophysically abundant multiply charged metallic element like iron, whose photoionization spectrum had not previously been observed.

DISCUSSION

In this experiment the use of synchrotron radiation and the merged-beams technique allowed the observation of Fe^{4+} photoions for the first time. The experiment is an important step in photoionization studies, because until recently the technical difficulties of producing well-characterized multicharged ion and photon targets of sufficient density impeded the study of photoionization of highly charged ions. These difficulties have now been overcome by combining a merged-beams apparatus, an electron-cyclotron-resonance (ECR) multicharged ion source and a third-generation synchrotron radiation source, at the 10.0.1 undulator beamline at the Advanced Light Source (ALS).

The results obtained in the experiment indicate that it is possible to produce Fe^{3+} ions using the evaporation of ferrocene ($C_{10}H_{10}Fe$) and the ECR source. The experiment demonstrated that it is possible to photoionize the Fe^{3+} ions to

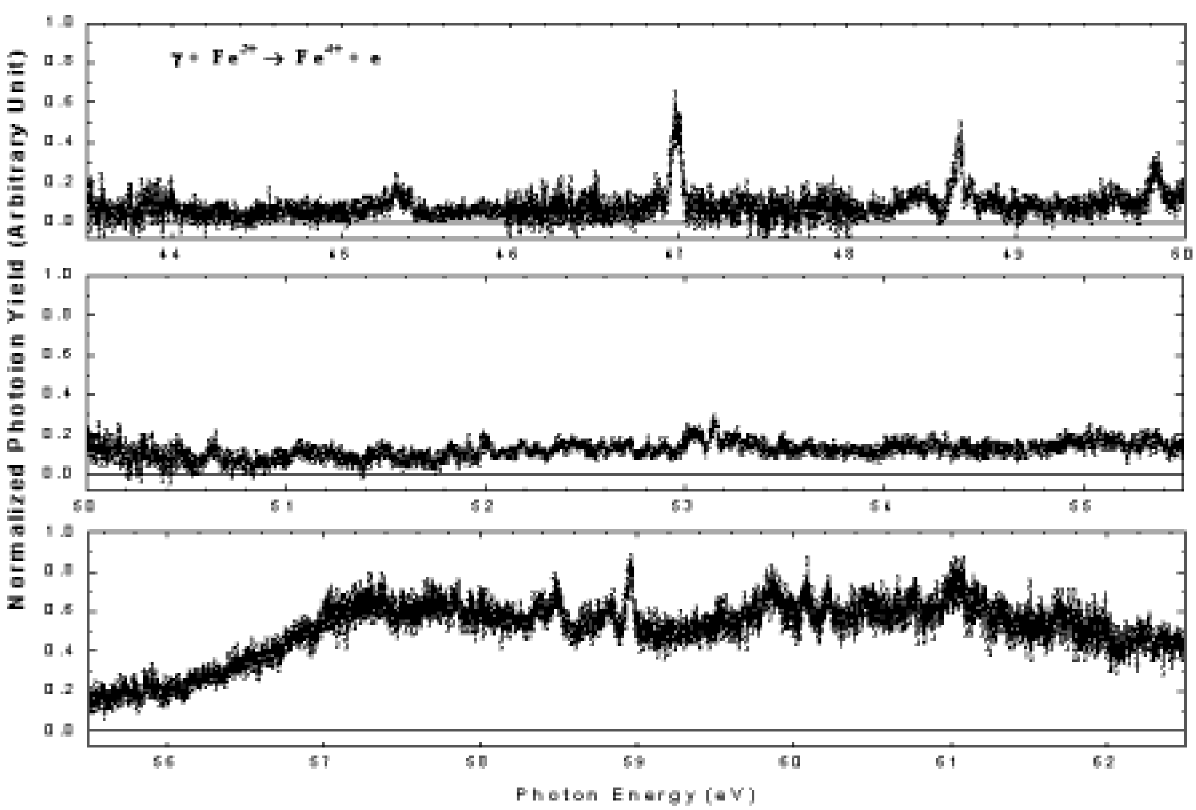

Figure 5: Graph of data collected on photoionization of Fe^{3+}.

create Fe^{4+}ions and to detect the photoions. The measurements of the relative yield of Fe^{4+} photoions as a function of the photon beam energy revealed the presence of resonance structures at certain energies. The energy positions and relative magnitudes of these resonance structures observed will serve as benchmarks for theory. Further photoionization studies of Fe^{3+} that are planned will place the present measurements on an absolute cross-section scale. These studies will also examine in depth each energy range were a resonance is present, and also the energy range of the ionization threshold (ionization potential). Such data will then be used to model various astrophysical phenomena like the propagation of light through the atmospheres of stars. They will also be helpful in interpreting light emissions from laboratory plasmas and from reactors that are being developed to extract energy from thermonuclear fusion reactions.

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